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Bond of Ribbed Bars Under High Cycle Repeated Loads

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To determine the bond behavior of ribbed bars under repeated loads, 308 pullout specimens were tested. The specimens failed by pulling out of the bars. In the tests the following parameters were varied: maximum load and load amplitude, bar diameter, concrete quality, and bond length. Furthermore, as a comparison, tests under sustained load were carried out. A repeated load has a similar influence on the bond as on the deformation and failure behavior of unreinforced concrete, and it accelerates, in comparison with a sustained load, the nonelastic deformation (slip).

Keywords: bond (concrete to reinforcement); cyclic loads; deformed reinforcement; fatigue (materials); pullout tests; reinforced concrete; stresses.

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INTRODUCTION

While the properties of concrete and steel under cyclic loading are known (1), the behavior of the bond between steel and concrete under repeated load has hardly been investigated and the results are contradictory.

In 1945 Muhlenbruch (2) carried out a great number of tests with pull-out specimens. The results showed a decrease in the pull-out resistance of the bar by about 50% when its anchorage has been submitted to 5×10^6 repeated tensile loadings, the maximum value being 50% of the failure load.

Verna and Stelson (3) tested beams. They suppose that the fatigue strength of bond for 10^6 load reversals is less than about 40% of the static strength, which is considerably lower than the fatigue strength of axially loaded concrete.

On the other hand the tests of Perry and Jundi (4) with eccentric pull-out specimens showed no decrease of the bond strength due to a preliminary cycling load. This result is confirmed by the tests of Tepfers (5) on beams with spliced reinforcement.

The aim of the tests reported here was the clarification of the above mentioned contradictions and also to provide answers to the following questions:

- How many load cycles as a function of the maximum and minimum load are possible before fatigue failure of bond occurs (fatigue strength of bond),
- how are the bond laws (relation between local slip and bond stress) and thus the service behavior of an anchorage changed by load reversals,
- how do preliminary repeated loadings influence the static strength of bond.

The two possible types of bond failure were studied whereby the bond failure due to shearing of the concrete between the ribs was studied by pulling the bars out of specimens with a large concrete cover and the bond failure due to splitting of the concrete cover was studied on beams with spliced reinforcement. In the following only the results of the pull-out tests are reported. The results of the tests with spliced reinforcement are described in references (6) and (7).

SPECIMENS

The reinforcing bars were cast centrally in concrete cylinders. The bond-free length on either side was 5 d_b, the bond length l_b was normally $3d_b$, but in some cases up to 18 d_b (fig. 1).

Hot rolled deformed bars from BSt 42/50 RU (fig. 2) with a nominal yield strength f_y = 420 N/mm^2 (60 000 psi) were used. The related rib area (relation bearing area/shearing area) according to Rehm (8) was about 0.075.

The following factors were varied:

bar diameter: d_b = 8 mm, 14 mm and 28 mm (0.3, 0.55 and 1.1 in),
compression strength of concrete (measured on cubes with a side length of 20 cm): f'_c = 23.5 N/mm^2 and 48.0 N/mm^2 (3350 and 6800 psi),
maximum load and load amplitude as a function of the static failure load.

TEST PROCEDURE AND MEASUREMENTS

Each series consisted of 7 specimens. The tests were started 4 to 5 weeks after casting. 3 specimens were loaded with a constant load increase until failure. The remaining 4 specimens were submitted to sinusoidal repeated loads, which were applied by a hydraulic pulsator. In case no failure occured during one million load reversals, the specimens were loaded in the same way as in the static test to failure. With a special test arrangement it was possible to test all 4 specimens simultanously.

Depending on the magnitude of the maximum load 30 to 70 load reversals per minute were applied.

The slip at the unloaded bar end was measured. In addition, on some specimens with a large bond length, the steel strain along the bond length was measured using electrical resistance strain gages analogous to the procedure described by Mains (9). Altogether 308 pull-out specimens were tested.

TEST RESULTS

Fatigue strength of bond

The observed number of load reversals until fatigue failure occured increased with decreasing maximum load for constant minimum load. This can be seen in fig. 3.

The tests with different bar diameters and concrete qualities are designated by different symbols. If no bond failure occured the point in the diagram is marked with an arrow. A number besides a symbol corresponds to the number of similar results.

The test results can be approximated by a straight line in a semi-logarithmic diagram. The scattering of the results corresponds approximately to those to be expected from fatigue tests. An influence of the concrete strength and the bar diameter on the fatigue strength could not be observed.

An increase of the lower load under otherwise constant conditions causes an increase of the service life, as does the reduction of the upper load. Therefore the mean stress and the stress range can be used as reference values for the description of the influence of repeated loads on bond. Fig. 4 shows the Smith diagram (10) for concrete under centrally applied load. It is valid for 2 million load reversals. The reported test results (extrapolated to 2×10^6 load reversals) are shown, as relative values, in form of circles. It can be seen that the fatigue strength of bond under repeated loading agrees well with that of concrete.

Behavior during load reversals

The slip at the free bar end increased considerably during the load cycling. The increase was mainly influenced by the upper load and the bond length. The basic behavior is represented in fig. 5 which shows the measured slip as a function of the number of load reversals. In each case the average slip of a test series has been recorded. The lower load was in all cases 10 percent of the ultimate load.

In a double-logarithmic diagram the results can be approximated by straight lines which, for loads below the fatigue strength of bond run approximately parallel to each other. On the other hand for the tests which failed by fatigue the gradient of the line increases.

The form of the slip-curves as a function of the number of load reversals corresponds to the usual laws for the time-dependent deformations of unreinforced concrete loaded in compression.

The slip s_n expected after a certain number of load reversals n can be calculated from the initial slip s_o by $s_n = s_o(1 + k_n)$. The slip coefficient k_n for loads below the fatigue strength of bond is for the test conditions used $k_n = (1 + n)^{0.107} - 1$ and is not greatly influenced by the parameter variations used. The ratio between the slip calculated on the basis of the above equations and the measured values is for all tests about 1.0 with a standard deviation of only 0.2.

Loading after load reversals

The specimens which sustained 10^6 load reversals without failure were afterwards loaded statically to failure. The average behavior of the specimens with short embedment length ($l_b = 3\ d_b$) and diameter of $d_b = 14$ mm (0.55 in) is represented in fig. 6. It shows the mean bond stress relative to the concrete strength (measured on cubes) as a function of the slip at the free bar end. The behavior for other test conditions was similar.

Curve ① represents a constantly increasing load until failure. If after reaching a predetermined load a repeated load is applied, the slip increases as described (curve ②). Curve ③ is valid for the static loading after load reversals. This law is characterized by a very steep gradient because the slip, to a great part, has already occured during the cyclic load. Shortly before reaching the line ① the curve deviates from the straight line and runs almost parallel to ①.

The bond strength as well as the maximum slip of preloaded specimens were on an average 5 % higher than those of the only statically loaded specimens. For the 27 evaluated test series the coefficient of variation for the ratio of the ultimate bond stresses is about 10%. The scattering of the failure slip values was greater.

The bond behavior of the specimens after load reversals corresponds to the deformation and failure behavior of preloaded centrally compressed concrete specimens (11).

Stress redistribution along the anchorage length

The local increase of the relative deformations between steel and concrete (slip) cause, according to the known bond laws, a stress redistribution within a given bond (anchorage) length. Fig. 7 represents an example for an upper load corresponding to 0.4 times the pull-out load. The bond stress under minium load was min $v_b = 0.1\ v_{bu}$. The number of load reversals n is chosen as a parameter.

Perry and Jundi (4) described similar results, but the present tests showed that after 10^3 load reversals an important change of the force distribution still occurs.

The influence of a repeated load on the steel and bond stresses as well as the slip along the anchorage length can be calculated by the method of Franke (12) using the laws represented in fig. 5.

Relation between sustained and cyclic load

For comparison some specimens were submitted to a sustained load of about 0.55 to 0.72 times the static failure load. In fig. 8 the mean slip of the three test series as a function of the loading time in hours is shown. For both axes a logarithmic scale was chosen. Furthermore the results of comparable test specimens submitted to an upper load corresponding to the sustained load and a lower load corresponding to 0.10 times the pull-out load are shown as a function of the number of load cycles. In order to eliminate the inevitable scattering in the slip which occurs at reaching the given load for the first time, average slip values were used.

As far as the slip is concerned the results show that a cyclic loading can be considered as a time accelerator compared with a sustained load. A similar behavior was found by Whaley and Neville (13) for creep tests with unreinforced concrete specimens.

SUMMARY AND CONCLUSIONS

The following conclusions can be drawn from the described tests:

1. Repeated load has a similar influence on the slip and the bond strength of deformed bars as on the deformation and failure behavior of unreinforced concrete.

2. The fatigue strength of bond corresponds to the fatigue strength of centrally loaded concrete. This means that no fatigue bond failure will occur during several million load reversals if for the usual anchorage lengths required for reinforcing bars the upper load is smaller than about 50 percent of the static pull-out load.

3. A preapplied repeated load, providing failure does not occur, does not negatively affect the deformation be-

haviour of the anchorages near failure or the ultimate load compared with a constant load increase in a static test.

4. If no fatigue failure occurs, a repeated load has only an influence on the bond behavior under service load. The increase of slip between steel and concrete causes a decrease of the local bond stiffness. The result is a redistribution of the forces along the anchorage length, which can also be expected under a sustained load of the same magnitude.

According to tests (5, 6, 7) on beams and slabs with a reinforcement spliced by overlapping, these conclusions are also valid in cases when the bond failure doesn't occur by pulling-out of the bars but by splitting off of the concrete cover.

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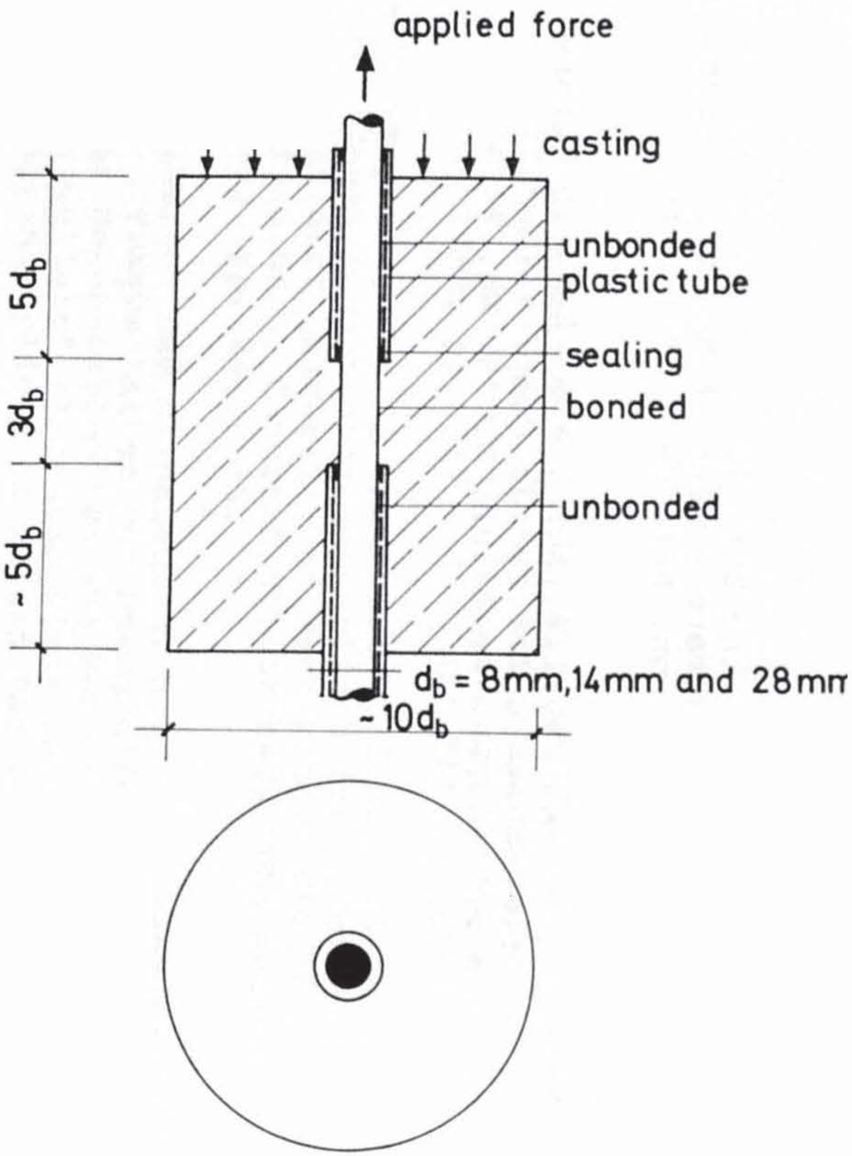

Fig. 1: Test specimen

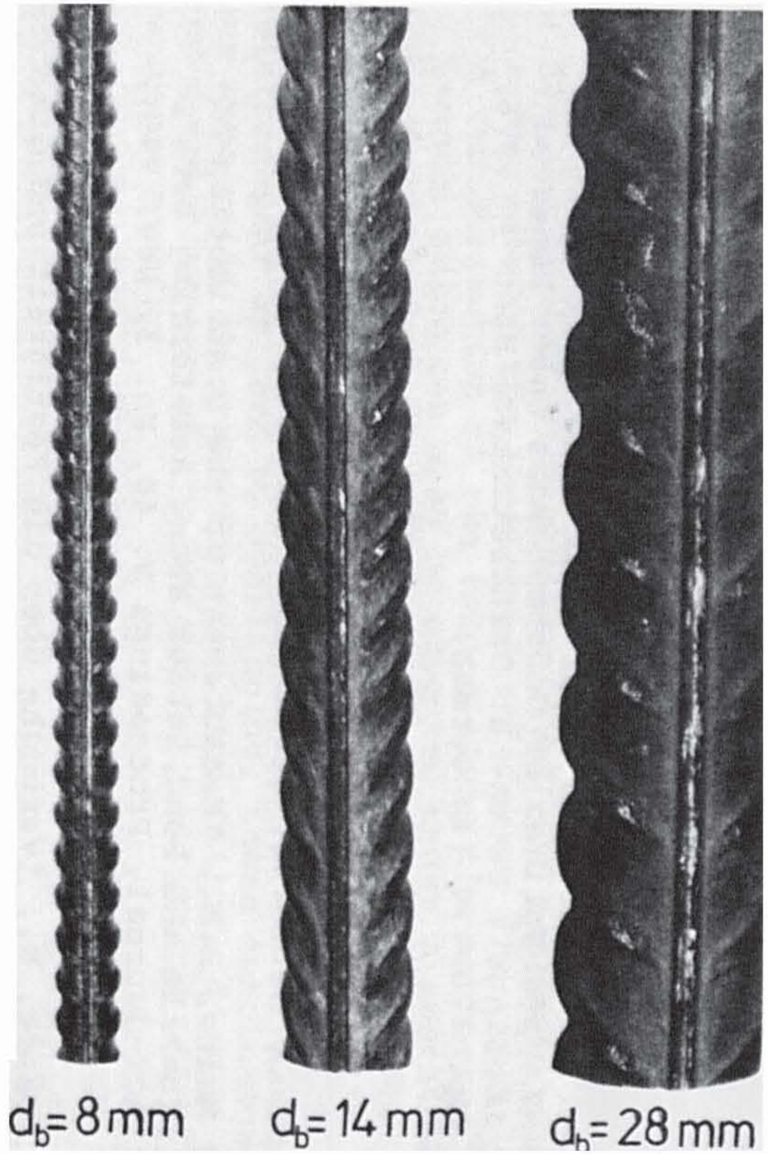

Fig. 2: Bars used for the tests

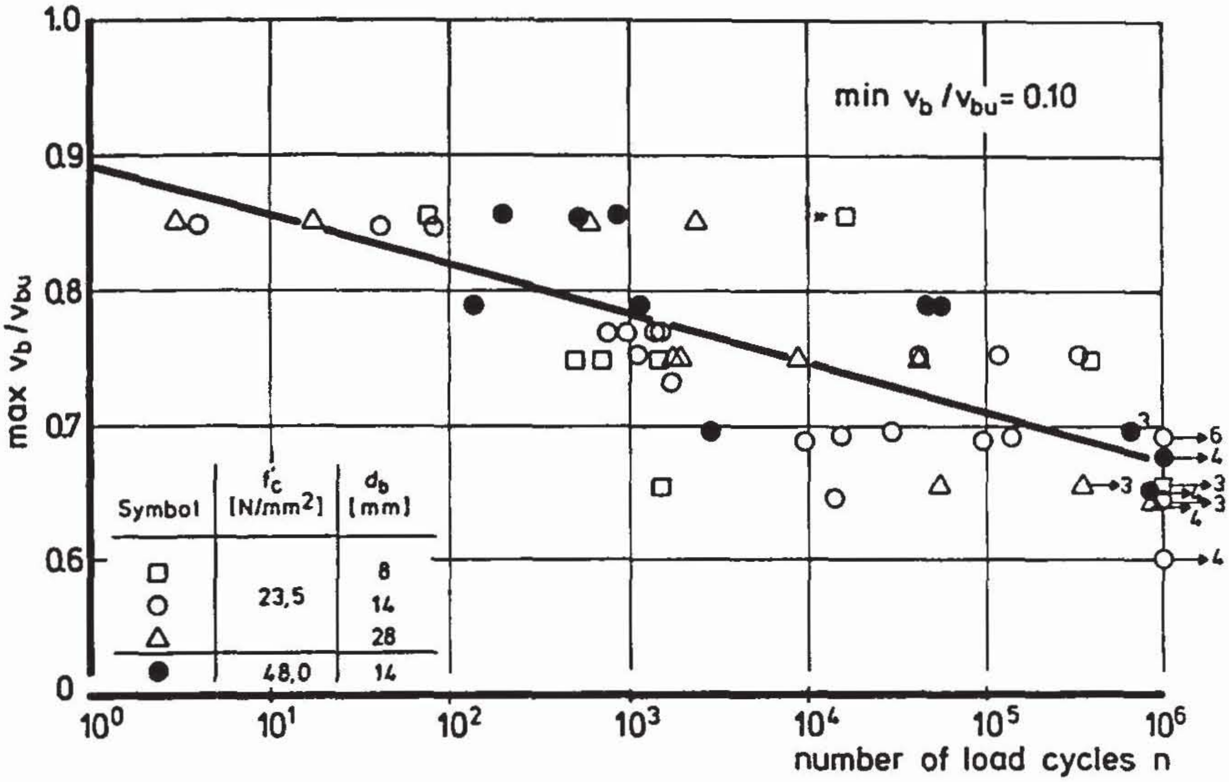

Fig. 3: Influence of the bond stress under upper load, max v_b, (related to the static bond strength v_{bu}) at constant lower load on the service life.

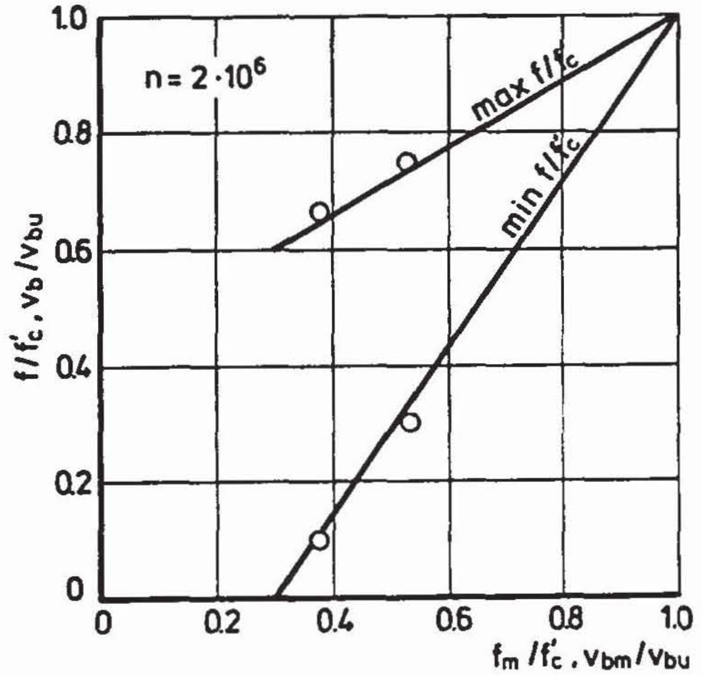

Fig. 4: Smith-diagram for concrete under cyclic compressive load and comparison with results of the pull-out tests (f_c' = concrete compression strength, measured on cylinders)

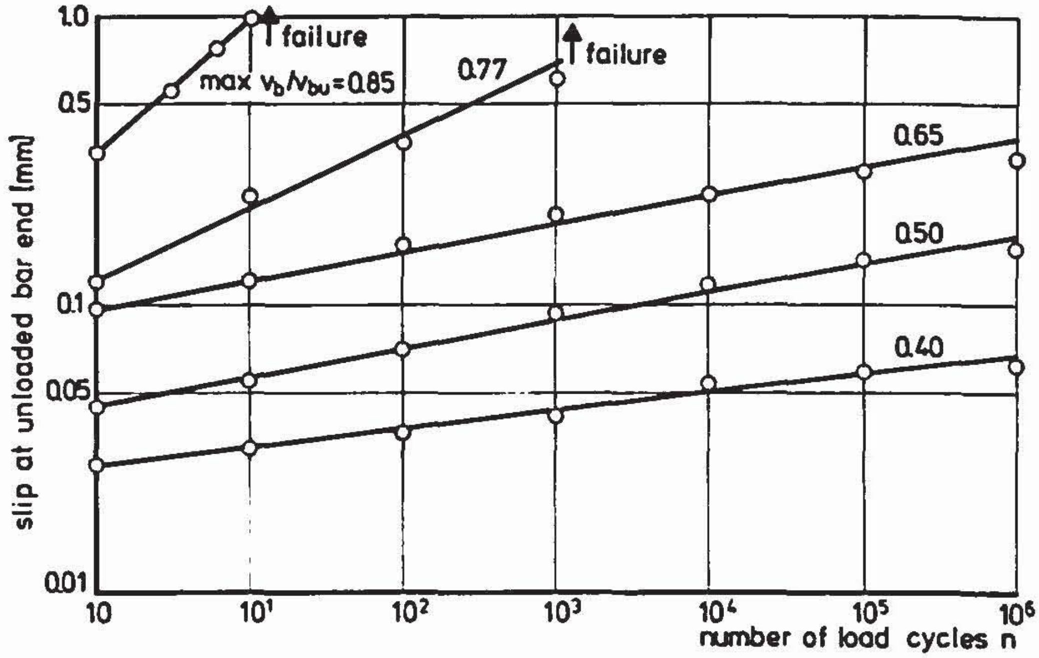

Fig. 5: Increase of slip at the free bar end during cycling load as a function of the number of load reversals n
(f'_c = 23.5 N/mm^2 (3350 psi), d_b = 14 mm (0.55 in), bond length 3 d_b)

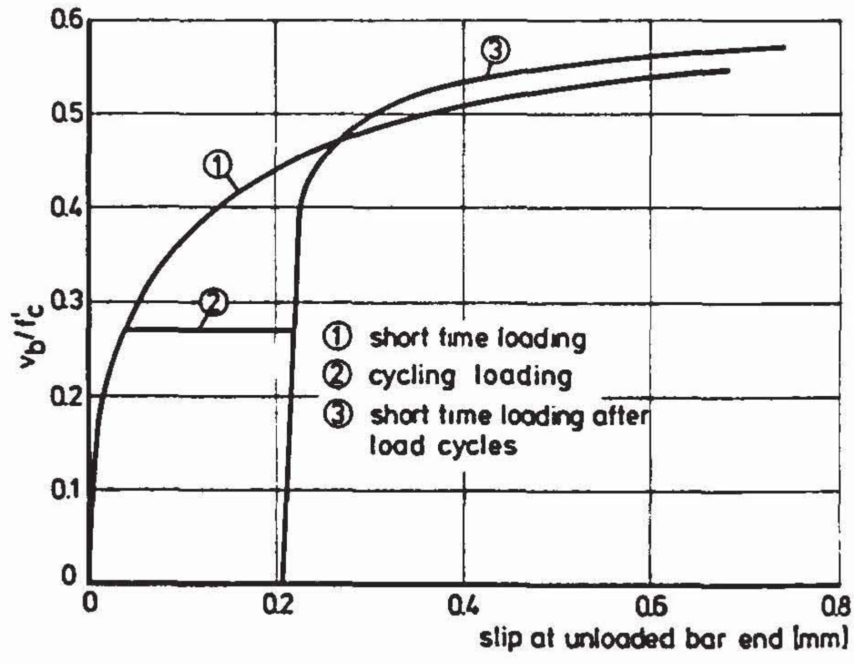

Fig. 6: Load - slip laws for the static test ①, under cyclic loading (v_b/v_{bu} = 0.5, n = 2 x 10^6) ② and for a static load after cyclic loading ③
(f'_c = 23.5 N/mm^2 (3350 psi), d_b = 14 mm (0.55 in), bond length 3 d_b)

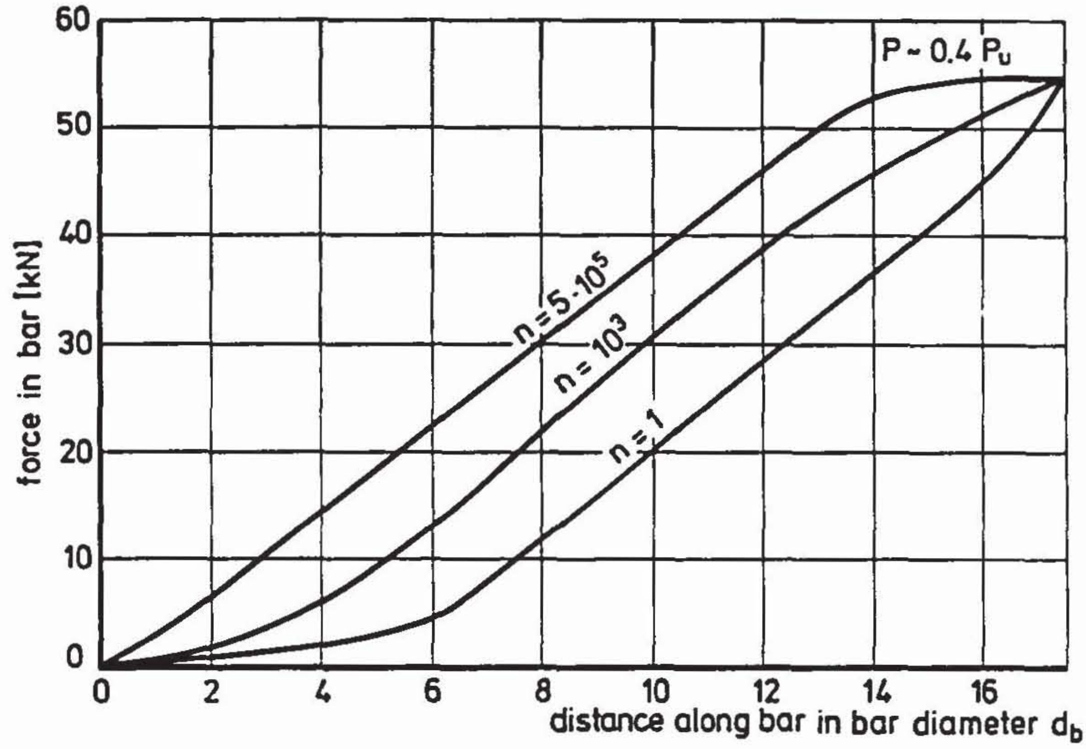

Fig. 7: Typical distribution of the bar forces along the bond length for different numbers of load reversals (f'_c = 24.6 N/mm^2 (3350 psi), d_b = 16 mm (0.62 in))

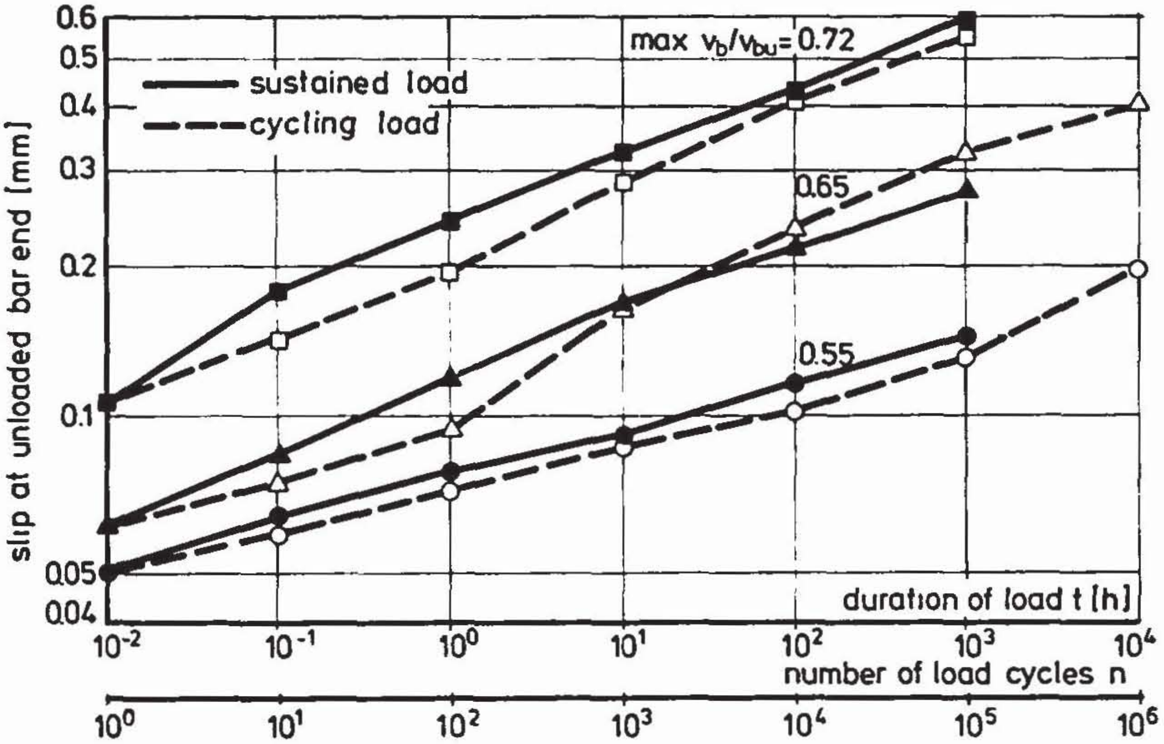

Fig. 8: Increase of slip at the free bar end during a static sustained load and a cycling load (f'_c = 48.0 N/mm^2 (6800 psi), d_b = 14 mm (0.55 in), bond length 3 d_b)